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ELASTIC-PLASTIC ANALYSIS OF A THICK-WALLED COMPOSITE TUBE SUBJECTED TO INTERNAL PRESSURE

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This report presents an elastic-plastic analysis of a thick-walled composite tube subjected to internal pressure. The composite tube is constructed of a steel liner and a graphite-bismaleimide outer shell. Analytical expressions for stresses, strains, and displacements are derived for all cases where the structure is subjected to internal pressure. The loading ranges include elastic, elastic-plastic, and fully-plastic up to failure. Numerical results for the hoop strains in several composite tubes are presented.

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INTRODUCTION

Organic composites have become familiar structural components in many applications that require high stiffness and low weight. A current problem in Army cannon design is to replace a portion of the steel wall thickness with an organic composite. The steel liner maintains the tube-projectile interface and shields the composite from the extremely hot gases. The steel also has elastic properties in the radial direction that are better than the composites for transferring loads. The theoretical and experimental results for an organic composite-jacketed steel tube subjected to internal pressure in the elastic range were described in a recent report (ref 1). This report presents an elastic-plastic analysis of the composite tube problem. The composite tube is constructed of a steel liner and a graphite-bismaleimide outer shell. Analytical expressions for stresses, strains, and displacements are derived for loading within and beyond the elastic range up to failure.

ELASTIC RANGE

Figure 1 shows a schematic of the composite tube problem. The composite tube consists of an inner steel "liner" and an outer composite "jacket." The

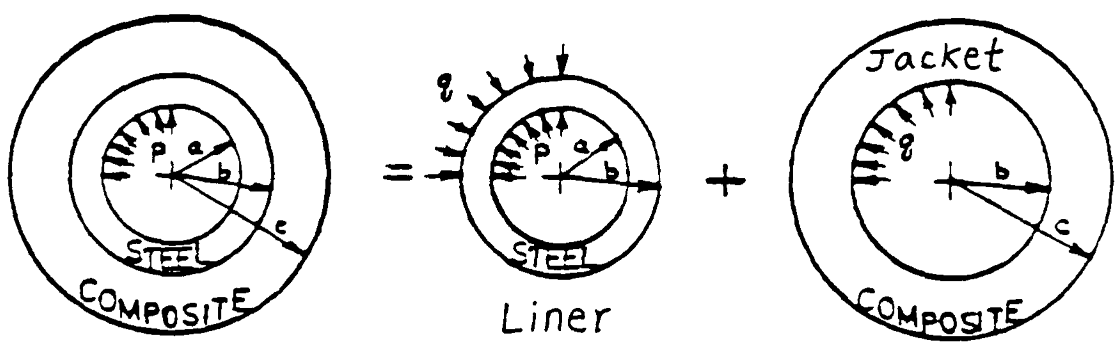

Figure 1. Schematic of a composite tube problem.

steel liner of inside radius a and outer radius b is wrapped in the circumferential direction with a graphite-bismaleimide organic composite of outside radius c. The elastic material constants for the composite and the steel are given in Table I.

TABLE I. ELASTIC CONSTANTS OF COMPOSITE JACKET AND STEEL LINER

Elastic Constants for IM6/Bismaleimide, 55% F.V.R.		
E_r = 1.126 Mpsi	$\nu_{r\theta}$ = 0.01524	$\nu_{\theta r}$ = 0.3155
E_θ = 23.31 Mpsi	$\nu_{\theta z}$ = 0.3155	$\nu_{z\theta}$ = 0.01524
E_z = 1.126 Mpsi	ν_{zr} = 0.3991	ν_{rz} = 0.3911
Elastic Constants for Steel		
E = 30.0 Mpsi	ν = 0.3	

When the composite tube is subjected to internal pressure p in the elastic range, the general solutions in the plane-strain condition for the isotropic liner ($a \leq r \leq b$) are

$$\begin{matrix}\sigma_r \\ \sigma_\theta\end{matrix} = \left\{\mp(p-q)\left(\frac{b}{r}\right)^2 + p - q\, b^2/a^2\right\}/\left(\frac{b^2}{a^2} - 1\right) \quad \begin{matrix}(1) \\ (2)\end{matrix}$$

$$u/r = E^{-1}(1+\nu)[(p-q)(b/r)^2 + (1-2\nu)(p-q\, b^2/a^2)]/\left(\frac{b^2}{a^2} - 1\right) \quad (3)$$

and for the orthotropic jacket ($b \leq r \leq c$),

$$\sigma_r = q[-\left(\frac{c}{b}\right)^{k-1}\left(\frac{c}{r}\right)^{k+1} + \left(\frac{r}{b}\right)^{k-1}]/[(c/b)^{2k} - 1] \quad (4)$$

$$\sigma_\theta = kq[(c/b)^{k-1}\left(\frac{c}{r}\right)^{k+1} + \left(\frac{r}{b}\right)^{k-1}]/[(c/b)^{2k} - 1] \quad (5)$$

$$u/r = \epsilon_\theta = \alpha_{12}\sigma_r + \alpha_{22}\sigma_\theta \quad (6)$$

where q is the pressure at the interface, $k = (\alpha_{11}/\alpha_{22})^{1/2}$,

$$\alpha_{11} = (1-\nu_{rz}\nu_{zr})/E_r$$

$$\alpha_{12} = -(\nu_{\theta r}+\nu_{\theta z}\nu_{zr})/E_\theta$$

$$\alpha_{22} = (1-\nu_{\theta z}\nu_{z\theta})/E_\theta \tag{7}$$

By requiring the displacement to be continuous at the interface, the interface pressure q can be expressed as a linear function of internal pressure p,

$$\frac{2p}{q} = (\frac{b^2}{a^2} - 1)[Ak \frac{(c/b)^{2k} + 1}{(c/b)^{2k} - 1} + B] + \frac{b^2}{a^2} + 1 \tag{8}$$

where

$$A = E\alpha_{22}/(1-\nu^2), \; B = -E\alpha_{12}/(1-\nu^2) - \nu(1-\nu) \tag{9}$$

Now all the stresses, strains, and displacements in the tube ($a \leq r \leq c$) can be determined as functions of p. In particular, the expressions for the displacements at the bore (u_a), interface (u_b), and outside surface (u_c) are

$$(\frac{b^2}{a^2} - 1) \frac{E}{p} \frac{u_a}{a} = (1+\nu) \frac{b^2}{a^2} + (1-\nu-2\nu^2) - \frac{4(1-\nu^2)(b^2/a^2)}{(\frac{b^2}{a^2} - 1)[AK \frac{(c/b)^{2k} + 1}{(c/b)^{2k} - 1} + B] + \frac{b^2}{a^2} + 1} \tag{10}$$

$$\frac{u_b}{b} = q[k\alpha_{22} \frac{(c/b)^{2k} + 1}{(c/b)^{2k} - 1} - \alpha_{12}] \tag{11}$$

$$\frac{u_c}{c} = \frac{2qk\alpha_{22}(c/b)^{k-1}}{(c/b)^{2k} - 1} \tag{12}$$

ELASTIC-PLASTIC RANGE

When the internal pressure p is large enough, part of the steel liner will become plastic. Using Tresca's yield criterion, the associated flow rule, and assuming linear strain-hardening, the elastic-plastic solution based on Bland can be used (refs 2,3). Let ρ be the elastic-plastic interface.

The solution can be written in the elastic portion ($\rho \leq r \leq b$) as

$$\frac{E}{\sigma_o} \frac{u}{r} = \frac{1+\nu}{2} \frac{\rho^2}{r^2} + (1-\nu-2\nu^2)[\frac{1}{2} \frac{\rho^2}{b^2} - \frac{q}{\sigma_o}] \tag{13}$$

$$\left.\begin{matrix}\sigma_r/\sigma_o \\ \\ \sigma_\theta/\sigma_o\end{matrix}\right\} = \mp \frac{\rho^2}{r^2} + \frac{\rho^2}{b^2} - \frac{q}{\sigma_o} \qquad \begin{matrix}(14)\\ \\ (15)\end{matrix}$$

$$\sigma_z/\sigma_o = \nu\ \rho^2/b^2 - 2\nu\ q/\sigma_o \tag{16}$$

and in the plastic portion ($a \leqslant r \leqslant \rho$)

$$\frac{E}{\sigma_o}\frac{u}{r} = (1-\nu-2\nu^2)\frac{\sigma_r}{\sigma_o} + (1-\nu^2)\frac{\rho^2}{r^2} \tag{17}$$

$$\left.\begin{matrix}\sigma_r/\sigma_o \\ \\ \sigma_\theta/\sigma_o\end{matrix}\right\} = \mp \frac{1}{2}\left(1-\eta\beta+\eta\beta\frac{\rho^2}{r^2}\right) + \frac{1}{2}\frac{\rho^2}{b^2} - (1-\eta\beta)\ln\frac{\rho}{r} - \frac{q}{\sigma_o} \qquad \begin{matrix}(18)\\ \\ (19)\end{matrix}$$

$$\sigma_z/\sigma_o = \nu\ \rho^2/b^2 - 2\nu(1-\eta\beta)\ln\frac{\rho}{r} - 2\nu\ q/\sigma_o \tag{20}$$

$$\bar{\epsilon}^p = \beta(\rho^2/r^2-1) \quad , \quad \eta\beta = \frac{m}{m + \frac{3}{4}\frac{(1-m)}{(1-\nu^2)}} \tag{21}$$

$$\eta = \frac{2}{\sqrt{3}}\frac{E}{\sigma_o}\frac{m}{1-m} \quad , \quad m = \frac{E_t}{E} \quad , \quad \sigma = \sigma_o(1+\eta\bar{\epsilon}^p) \tag{22}$$

where σ_o is the initial tensile yield stress and E_t is the tangent modulus in the plastic range of the stress-strain curve.

Using Eqs. (11) and (13) and the requirement of displacement continuity at the interface, i.e., u_{b-} (liner) = u_{b+} (jacket), we obtain the expression for the interface pressure q as

$$\frac{q}{\sigma_o} = \frac{(1-\nu^2)\rho^2/b^2}{(1+\nu)(1-2\nu) + E\left[\alpha_{22}k\frac{(c/b)^{2k}+1}{(c/b)^{2k}-1} - \alpha_{12}\right]} \tag{23}$$

Given any value of ρ in $a \leqslant \rho \leqslant b$, we can now determine q, u, and all the stresses and strains in the tube. In particular, the expressions for internal pressure and for displacements at the bore and the interface are

$$\frac{p}{\sigma_o} = \frac{q}{\sigma_o} + \frac{1}{2}\left(1 - \frac{\rho^2}{b^2}\right) + (1-\eta\beta)\ln\frac{\rho}{a} + \frac{1}{2}\eta\beta\left(\frac{\rho^2}{a^2} - 1\right) \tag{24}$$

$$\frac{E}{\sigma_o}\frac{u_a}{a} = -(1-\nu-2\nu^2)\frac{p}{\sigma_o} + (1-\nu^2)\rho^2/a^2 \tag{25}$$

$$\frac{E}{\sigma_o}\frac{u_b}{b} = (1-\nu^2)\frac{\rho^2}{b^2} - (1-\nu-2\nu^2)\frac{q}{\sigma_o} \quad (26)$$

By letting ρ = a and b, we can determine the lower limits p^*, q^*, u_a^*, u_b^*, u_c^*, and the upper limits p^{**}, q^{**}, u_a^{**}, u_b^{**}, u_c^{**}, respectively.

FULLY-PLASTIC RANGE

When the internal pressure p is further increased, i.e., $p > p^{**}$, the steel liner will become fully-plastic. The composite jacket remains elastic as long as the failure pressure is not reached. A fully-plastic solution is derived below.

Subject to $\sigma_\theta \geqslant \sigma_z \geqslant \sigma_r$, Tresca's criterion states that yielding occurs when

$$\sigma_\theta - \sigma_r = \sigma \quad (27)$$

where σ is the yield stress. For a linear strain-hardening material,

$$\sigma = \sigma_o(1+\eta\bar{\epsilon}^p) \quad (28)$$

where σ_o, η, $\bar{\epsilon}^p$, are the initial yield stress, hardening parameter, and equivalent plastic strain, respectively. The associated flow rule states that, subject to $\sigma_\theta > \sigma_z > \sigma_r$,

$$d\epsilon_\theta{}^p = -d\epsilon_r{}^p \geqslant 0 \quad \text{and} \quad d\epsilon_z{}^p = 0 \quad (29)$$

$de_z{}^p$ is an increment of plastic strain and is defined by $d\epsilon_z{}^p = d\epsilon_z - d\epsilon_z{}^e$. Since $d\epsilon_z{}^p = 0$, $d\epsilon_z = d\epsilon_z{}^e$, and therefore

$$\epsilon_z = \epsilon_z{}^e = (\sigma_z-\nu\sigma_r-\nu\sigma_\theta)/E \quad (30)$$

In the plane-strain case ($\epsilon_z = 0$) and using the equation of equilibrium,

$$\sigma_\theta = \sigma_r + r\sigma_r' \quad \text{and} \quad \sigma_r' = d\sigma_r/dr \quad (31)$$

we have

$$\sigma_z = 2\nu\sigma_r + \nu r\sigma_r' \quad (32)$$

Since the dilatation is purely elastic

$$u' + u/r + \epsilon_z = E^{-1}(1-2\nu)(\sigma_r+\sigma_\theta+\sigma_z) \tag{33}$$

Substituting from Eqs. (31) and (32)

$$u' + u/r = E^{-1}(1-2\nu)(1+\nu)(2\sigma_r+r\sigma_r') \tag{34}$$

On integration,

$$ru = E^{-1}(1-2\nu)(1+\nu)r^2\sigma_r + \phi\, b^2 \tag{35}$$

where

$$\phi = u_b/b + (1-2\nu)(1+\nu)E^{-1}q \tag{36}$$

Using Hooke's law and Eqs. (27), (28), (31), and (32), we obtain

$$E\epsilon_\theta^{\,e} = (1-2\nu)(1+\nu)\sigma_r + (1-\nu^2)\sigma_o(1+\eta\bar{\epsilon}^p) \tag{37}$$

Substituting from Eq. (35) for ϵ_θ and from Eq. (37) for $\epsilon_\theta^{\,e}$

$$\epsilon_\theta^{\,p} = \epsilon_\theta - \epsilon_\theta^{\,e} = \phi\, b^2/r^2 - E^{-1}(1-\nu^2)\sigma_o(1+\eta\bar{\epsilon}^p) \tag{38}$$

By Eq. (29) and the definition of equivalent plastic strain,

$$\bar{\epsilon}^p = \int d\bar{\epsilon}^p = \sqrt{\frac{2}{3}} \int \{(d\epsilon_\theta^{\,p})^2 + (d\epsilon_r^{\,p})^2\}^{1/2} = \frac{2}{\sqrt{3}}\, \epsilon_\theta^{\,p} \tag{39}$$

Combining Eqs. (38) and (39) leads to

$$\bar{\epsilon}^p = \frac{2}{\sqrt{3}}\, [\phi\, b^2/r^2 - (1-\nu^2)\sigma_o/E]/[1 + \frac{2}{\sqrt{3}}\, (1-\nu^2)\eta\sigma_o/E] \tag{40}$$

Substituting Eqs. (27) and (28) into Eq. (31) and integrating, we have

$$\sigma_r = -p + \sigma_o \ln(r/a) + \sigma_o\, \eta \int_a^r \bar{\epsilon}^p r^{-1}\, dr \tag{41}$$

Now using Eq. (40), an explicit expression for the radial stress is obtained

$$\sigma_r = -p + \sigma_o(1-\eta\beta)\ln(\frac{r}{a}) + \frac{1}{2}\, \frac{\eta\beta}{(1-\nu^2)}\, [\frac{b^2}{a^2} - \frac{b^2}{r^2}]E\phi \tag{42}$$

Using Eqs. (11) and (36) and the requirement of displacement continuity at the interface, i.e., u_{b-} (liner) = u_{b+} (jacket), we get

$$\phi = [E\alpha_{22}k \frac{(c/b)^{2k} + 1}{(c/b)^{2k} - 1} - E\alpha_{12} + (1-2\nu)(1+\nu)]q/E \qquad (43)$$

Evaluating σ_r at the interface from Eq. (42) and using Eq. (43), we obtain the relation between p and q

$$p = \sigma_0(1-\eta\beta)\ln \frac{b}{a} + q\{1 + \frac{1}{2}\eta\beta(\frac{b^2}{a^2} - 1)[Ak \frac{(c/b)^{2k} + 1}{(c/b)^{2k} - 1} + B + 1]\} \qquad (44)$$

It is interesting to point out that p is a linear function of q. Similarly, when evaluating u at the bore from Eq. (35), we obtain

$$u_a/a = -(1-2\nu)(1+\nu)P/E + \phi\, b^2/a^2 \qquad (45)$$

which can also be expressed as a linear function of q with the aid of Eqs. (43) and (44). Since the relation between q and u_b is linear from Eq. (11), p and u_a, given by Eqs. (44) and (45), respectively, can be expressed as linear functions of u_b.

NUMERICAL RESULTS

Given any value of internal pressure, we can obtain numerical results for the stresses and strains in the radial and tangential directions and also for the displacement at any radial position in a composite tube. However, only those values at the bore, interface, and outside surface have been calculated. The organic composite material is considered to be elastic until brittle failure occurs at a maximum strain of 1.3 percent. The steel is assumed to be elastic-plastic, linear strain-hardening with σ_0 = 120 Ksi, E_t = 0.04 E, and σ_u (ultimate stress) = 140 Ksi.

The relations between bore hoop strain and internal pressure are presented in Figures 2 and 3. Figure 2 shows the relations for four tubes of wall ratio 1.321 and Figure 3 for three tubes of wall ratio 1.546. The percentage of composite in each tube is defined by (c-b)/(c-a) x 100 percent. The relation between hoop strain and internal pressure is nonlinear in the elastic-plastic range and the two limits are indicated in the figures. The nonlinear range becomes smaller as the percentage of composite increases. For a given strain in the elastic range, the steel tube can resist larger pressure than the composite tube. However, for a large strain in the fully-plastic range, the composite tube can support larger pressure than the steel tube. This advantage in containing higher pressure seems very attractive for using composite tubes. It is also interesting to note that the nonlinear elastic-plastic range becomes larger as the wall ratio increases as shown in these two figures.

The numerical results for the hoop strains at the bore, interface, and outside surface of three composite tubes are shown in Figures 4, 5, and 6 as functions of internal pressure. The actual specimens were constructed (ref 1) using steel liners with two thicknesses and the appropriate thickness of the composite circumferentially wound on the liner. The geometric dimensions (a,b,c) for the three composite tubes are (0.9, 1.0, 1.189), (0.9, 1.07, 1,189), and (0.9, 1.07, 1.391). Figures 4, 5, and 6 show the numerical results for these tubes, respectively. The complete (including elastic, elastic-plastic, and fully-plastic) ranges of loadings up to failure pressure have been considered. Brittle failure of the composite material occurs at a maximum strain of 1.3 percent. The maximum values of internal pressure these three tubes can contain without failure are 56.9, 53.1, and 78.0 Ksi, respectively. In these figures we also show the limits of internal pressure in the elastic-plastic range, i.e., (p*, P**) = (20.48, 23.93), (23.06, 28.75), and (27.47, 34.98 Ksi), respectively.

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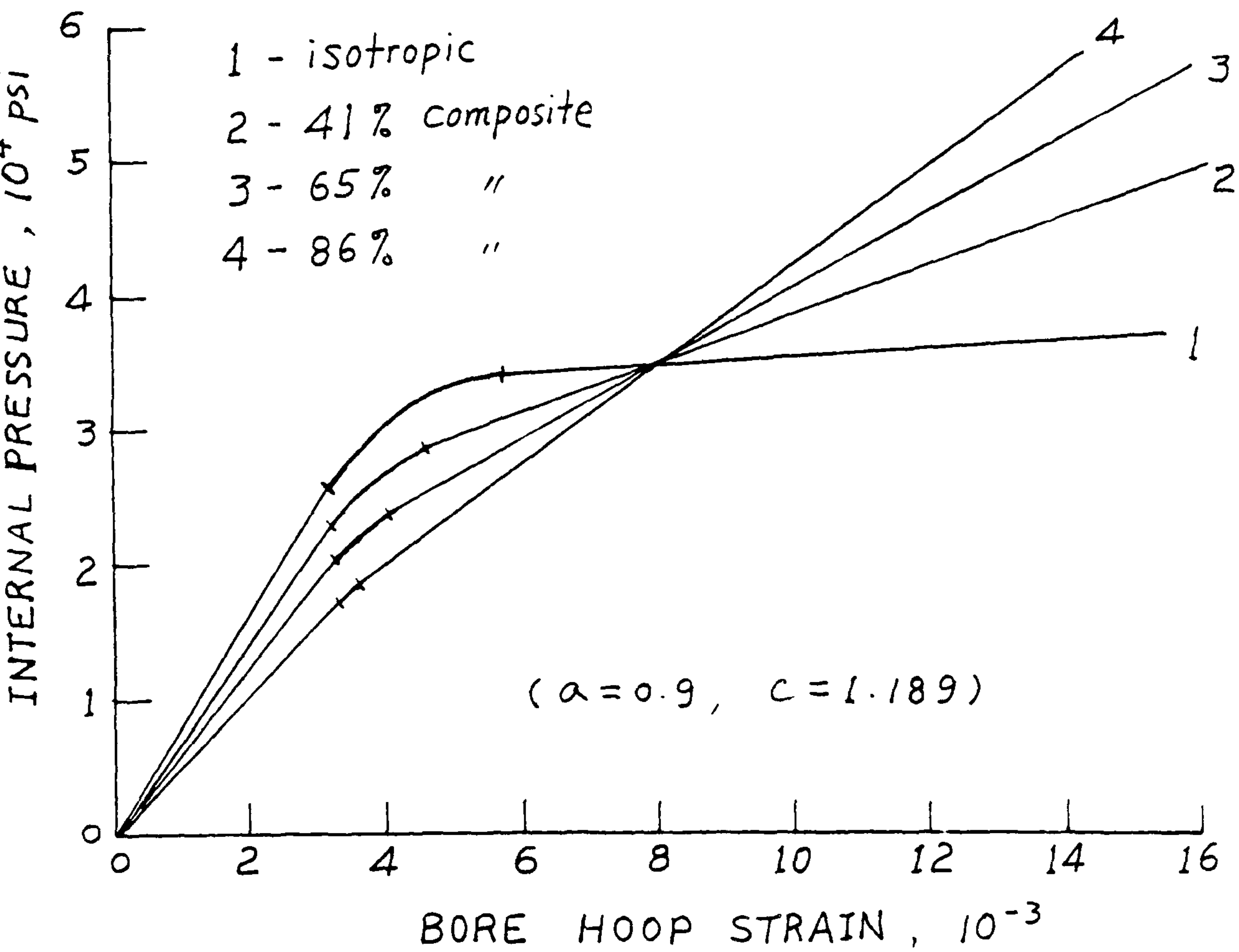

Figure 2. The relation between bore hoop strain and internal pressure for four tubes of wall ratio 1.321.

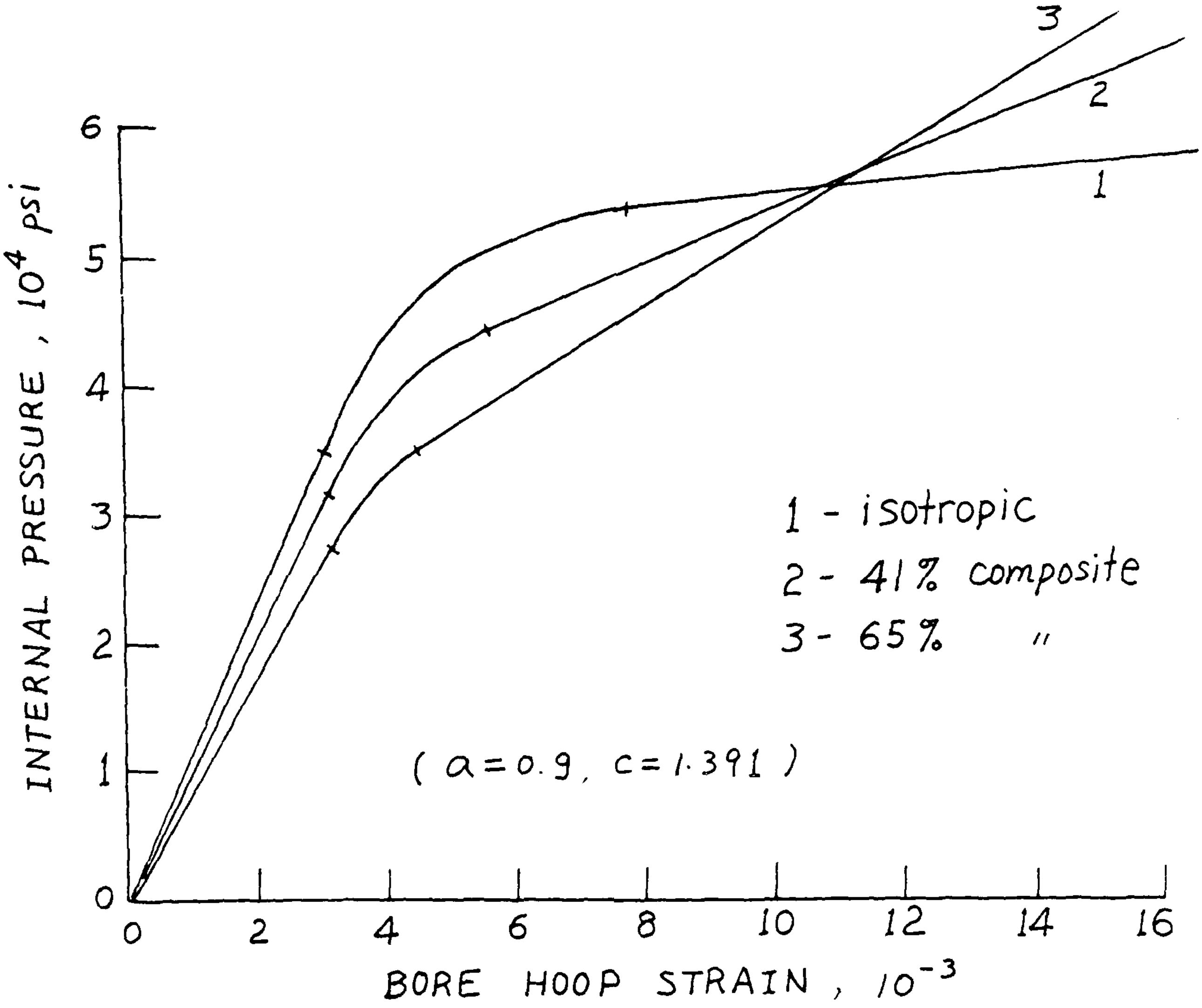

Figure 3. The relation between bore hoop strain and internal pressure for three tubes of wall ratio 1.546.

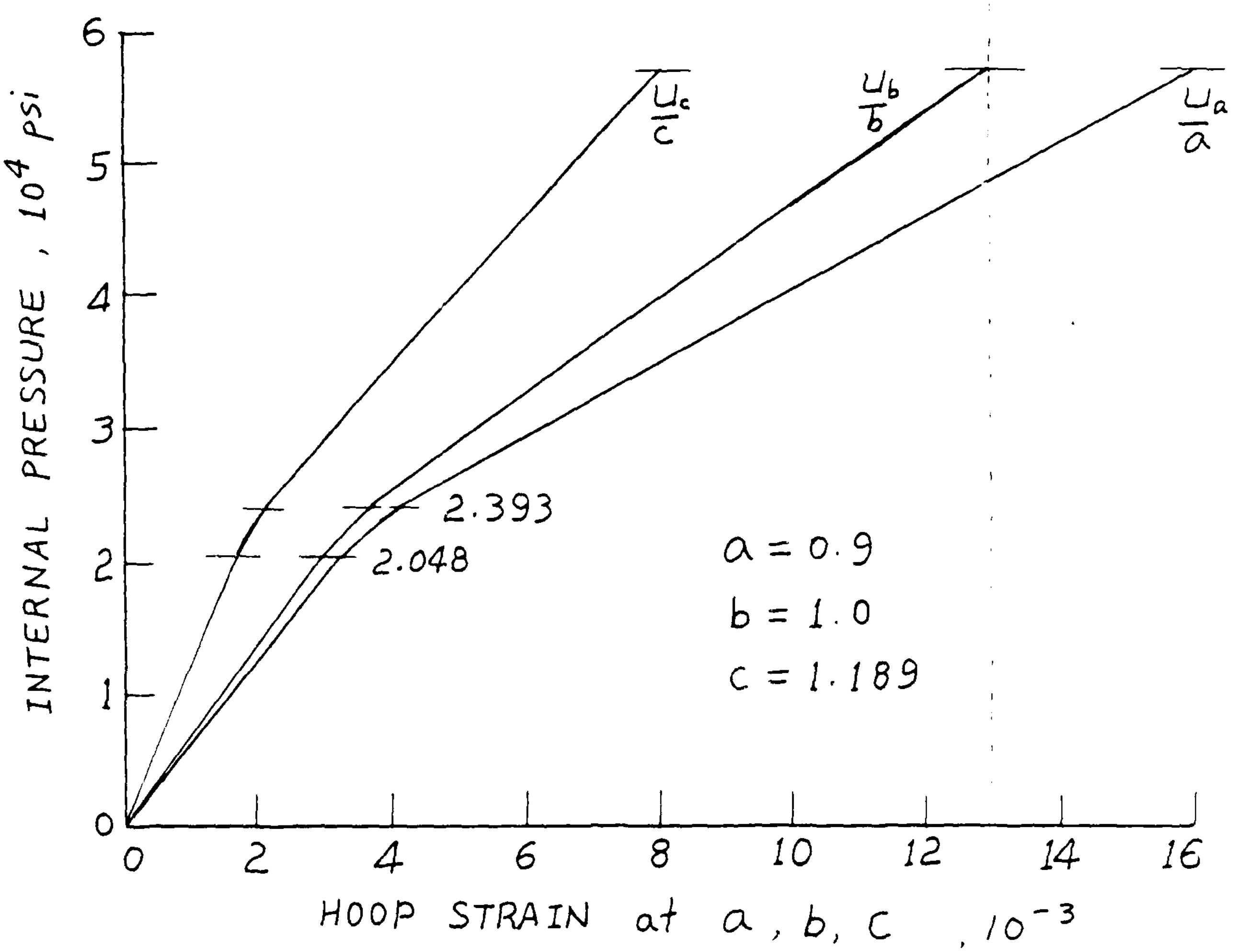

Figure 4. Hoop strains at the bore, interface, and outside surface as functions of internal pressure for a composite tube ($a = 0.9$, $b = 1.0$, $c = 1.189$).

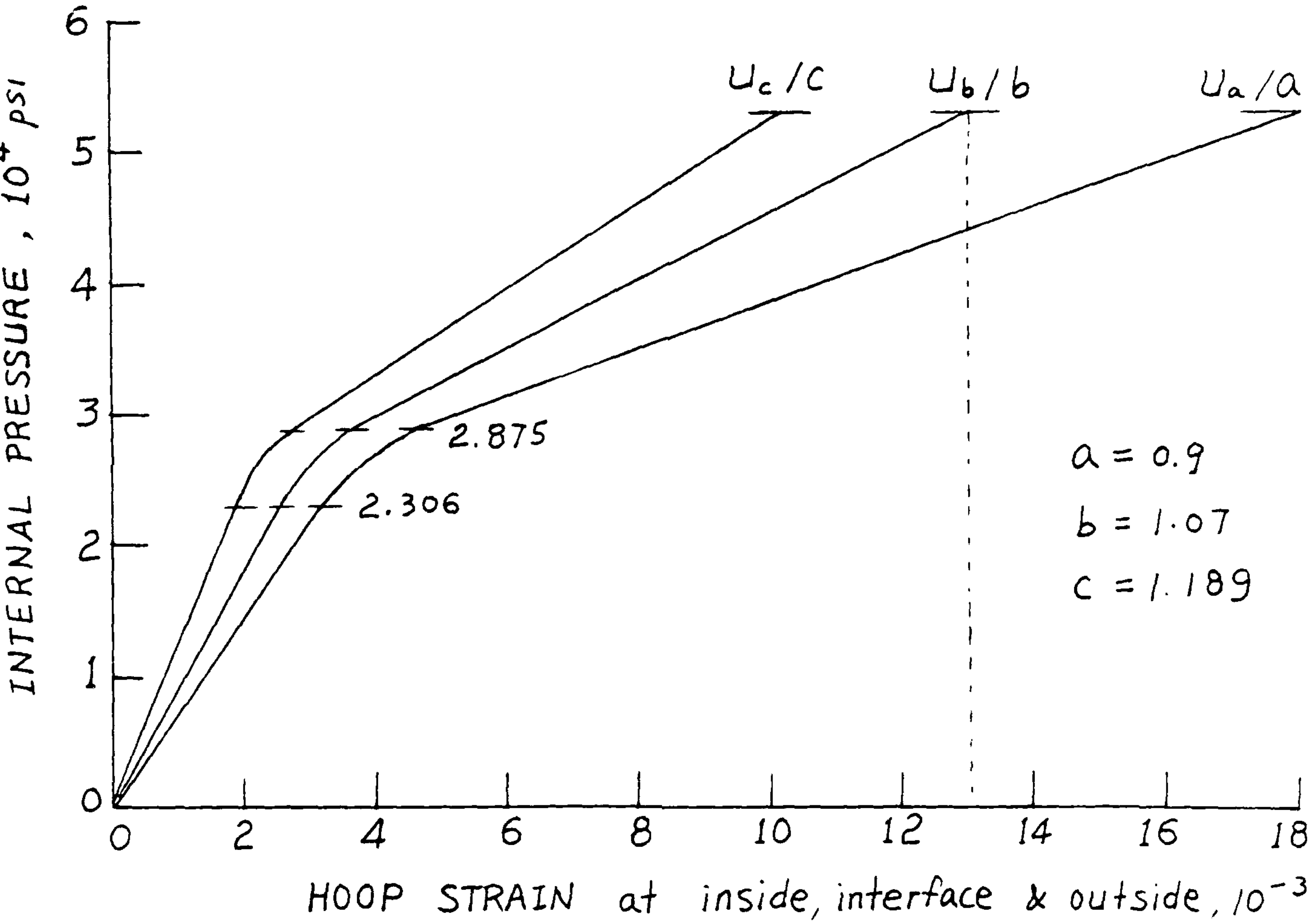

Figure 5. Hoop strains at the bore, interface, and outside surface as functions of internal pressure for a composite tube (a = 0.9, b = 1.07, c = 1.189).

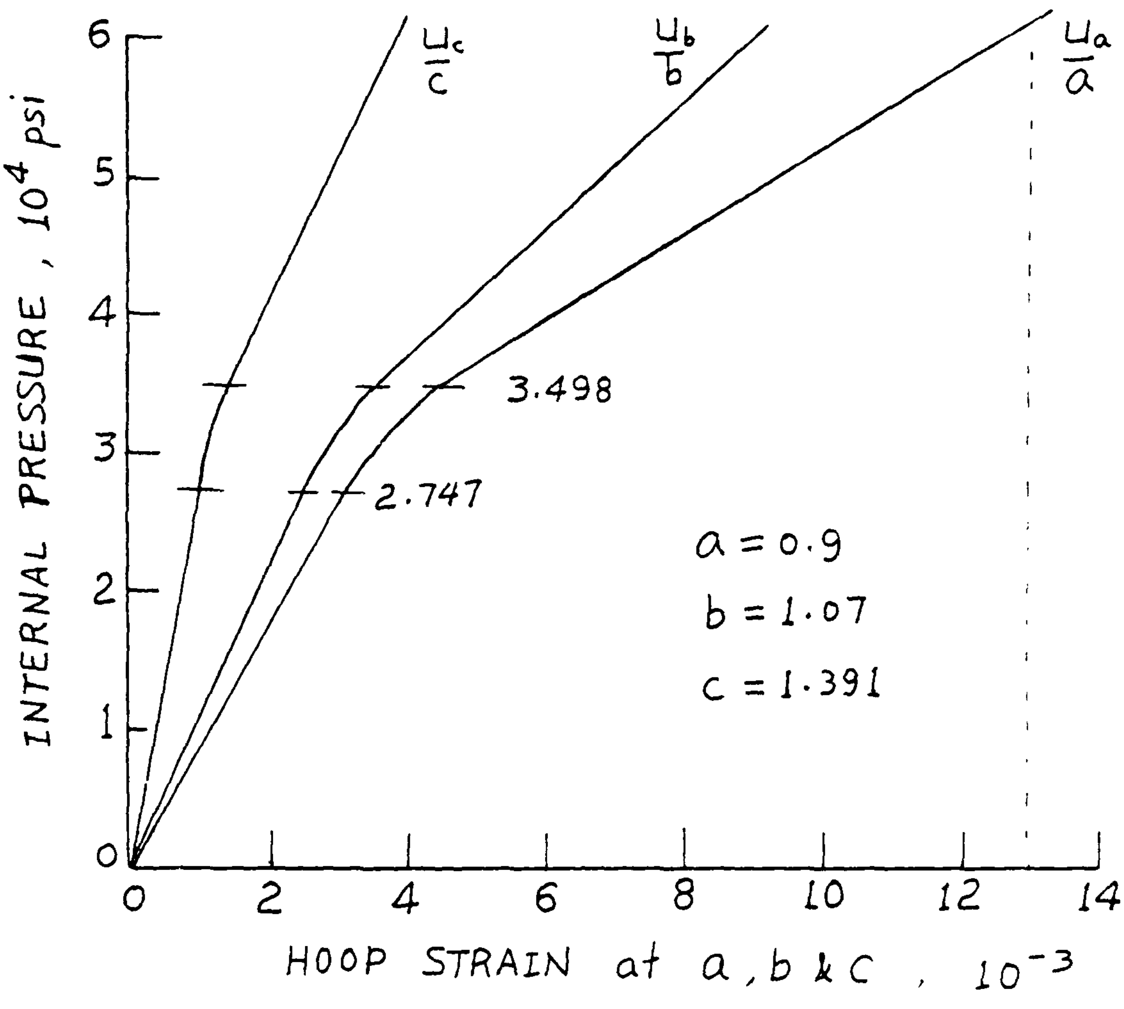

Figure 6. Hoop strains at the bore, interface, and outside surface as functions of internal pressure for a composite tube (a = 0.9, b = 1.07, c = 1.391).

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NOTE: PLEASE NOTIFY COMMANDER, ARMAMENT RESEARCH, DEVELOPMENT, AND ENGINEERING CENTER, US ARMY AMCCOM, ATTN: BENET LABORATORIES, SMCAR-CCB-TL, WATERVLIET, NY 12189-4050, OF ANY ADDRESS CHANGES.